

LIGHTWEIGHT THERMAL INSULATION FOR MARS SURFACE APPLICATIONS

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ABSTRACT

A lightweight thermal insulation design for Martian surface applications has undergone initial investigation and has been deemed ready for flight applications. The ambient Martian atmosphere, which is predominantly CO₂ at pressures between 5 and 10 torr, is used as the insulating medium with a modest multiple radiation shield enclosure. The insulation gap is accomplished by standing off the radiation shield enclosure from the hardware with Mylar spacers. This thermal insulation is lighter, less expensive, and much faster to fabricate and to install on Mars surface robotic vehicles (e.g., landers and rovers) and their payloads than insulation schemes used on previous Mars missions (e.g., fiberglass batt material, Aerogel, and Eccofoam). The insulating performance of the new insulation is 38% better than traditional insulations. In addition, this novel insulation is 60% lighter, 33% less costly, and 75% faster to fabricate and install on the hardware.

The intent of this paper is to present this novel insulation design approach, to report the comparison testing against fiberglass batt material, and to summarize the design parameters such as effective thermal conductivity, mass, cost, and delivery time for

the fiberglass batt material and this new insulation.

INTRODUCTION

The currently demonstrated-safe landing approach for Mars surface missions involves a direct ballistic entry with successive deceleration methods (i.e., aerobraking, parachute, solid rockets, and air bags). Hence, such missions are mass constrained. Given NASA's schedule to launch a Mars mission every 26 months, cost and schedule also become constraints. Engineers at the Jet Propulsion Laboratory (JPL) developed a new thermal insulation for Mars surface application that uses the *in-situ* CO₂. The thermal conductivity of CO₂ is less than insulation systems used on previous Mars missions (e.g., Aerogel and batt material). Since CO₂ is naturally available on the Martian surface, it need not be brought from Earth. Aerogel insulation requires an enclosure for structural support whereas CO₂ only requires a non-structural containment barrier. A larger mass of fiberglass batt material is needed to achieve an insulating performance equivalent CO₂. Finally, the convective heat transfer within the containment barrier is virtually negligible for gap widths up to 6 cm.

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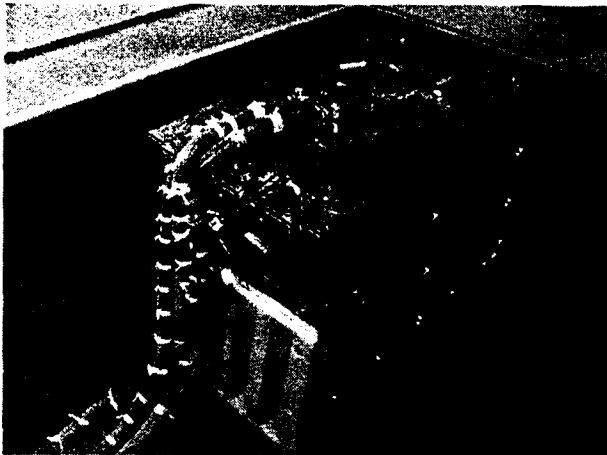


Figure 1 – MSP'01 PEB engineering model with thermal isolation mounts and cabling mockup

The analysis and comparative testing of this new insulation system is presented herein. The Mars Surveyor Program 2001 Lander payload electronics box with the dimensions of 25.3 cm x 16.1 cm x 17.0 cm was used in this study (see Fig. 1). The new insulation was compared against fiberglass batt insulation. Results from both analysis and test demonstrate that the new insulation is 60% lighter in mass, 33% lower in cost, and 75% faster to fabricate and install on the hardware than fiberglass batt insulation with a 38% improvement in insulation performance.

INSULATION DESCRIPTION

When an appreciable atmosphere exists, thermal engineers prefer bulk insulation such as fiberglass batting and Aerogel to multi-layer insulation (MLI) blanketing. Bulk insulation provides an excellent thermal barrier, but its mass is higher than MLI blanketing. When comparing the thermal conductivity of the candidate Martian surface insulations with the major Martian atmospheric constituent, CO_2 , one can conclude that stagnant CO_2 would be an effective thermal insulator (see Fig. 2). Since the CO_2 is readily available on the Mars surface, a CO_2 insulation holds the potential of being lighter than traditional bulk insulation

schemes (having the same insulating performance). Development of a gas entrapment design and negating free convection within the entrapped CO_2 remain as the major challenges for such an insulation system.

Gas Entrapment Design

A minimal-thickness MLI blanket can serve as the CO_2 containment barrier by borrowing an installation technique for standing-off MLI blankets to provide micro-meteoroid protection. Formed Mylar "bumpers" are attached to the hardware in strategic support locations (see Fig. 3) and then the MLI blanket is installed over these bumpers. The conductive path through the bumpers is negligible due to the cross-sectional area and path length. When the hardware is on the Martian surface, the gap created by the bumpers will fill with the Martian atmosphere (predominately CO_2). The height of the bumpers dictates the thickness of the CO_2 insulation. Radiative heat exchange is reduced by applying a low emittance finish to the hardware and using a low emittance finish

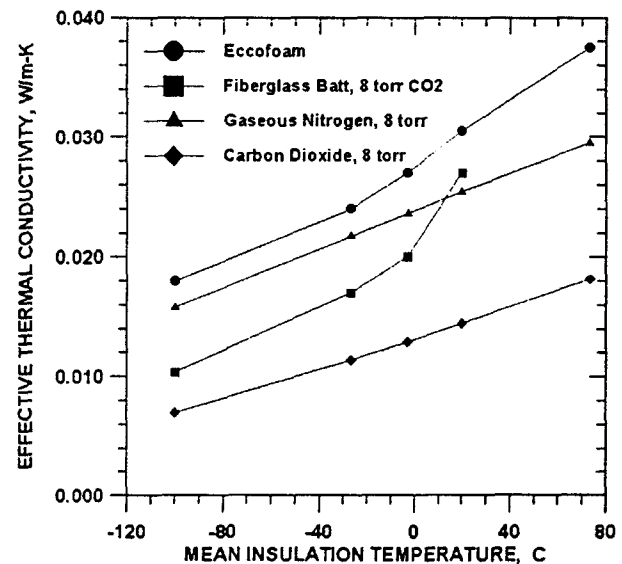


Figure 2 - Effective thermal conductivity of Martian surface insulations compared with gaseous nitrogen and carbon dioxide at 8 torr

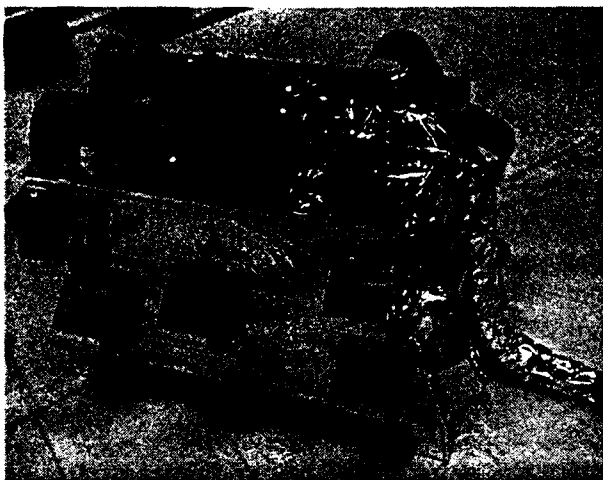


Figure 3 - Mylar bumpers are used to provide carbon dioxide gap spacing with low emittance finish on hardware to minimize radiation

on the inner most layer of the MLI blanket (which is typical of the MLI blanket inner layer).

This insulation system shows more flexibility in accommodating a wide spectrum of hardware geometries since the MLI blanketing is easily tailorable. Aerogel requires rigid containment approaches because of its tenuous nature. Fiberglass batting must be formed or reinforced using processes that are more labor intensive than the MLI blanket tailoring. Hence, this new proposed insulation has the potential to reduce cost and delivery schedule.

Free Convection Effects

The entrapped CO₂ gap insulation is predicated upon the gas being stagnant (i.e., no free convection). By using representative hardware dimensions and temperatures, a free convection analysis demonstrates that gas conduction is the dominant mode of heat transfer.

As a point of departure, the payload electronics box (PEB) from the recently canceled Mars Surveyor Program 2001 (MSP '01) Lander (25.3 cm x 16.1 cm x 17.0 cm) that would be directly exposed to the Martian

thermal environment represents an excellent evaluation candidate since fiberglass batt insulation characterization testing was previously conducted (see Fig 1). The PEB is thermally isolated from its thermal environment by G-10 structural mounts and the fiberglass batt insulation. The PEB thermal design must contend with the PEB cabling which represents a major heat loss. During the Martian nighttime, a typical minimum non-operating allowable flight temperature limit for the bulk average case is -50°C. During the nighttime when electrical power is a precious resource, the PEB mounting interface is expected to reach -85°C. The minimum Martian atmospheric temperature for MSP'01 Lander mission is expected to be -93°C. Using the theory for free convection in enclosed spaces, heat transfer across the CO₂ gap occurs only by conduction when the Grashof-Prandtl number (GrPr) product is less than 2000 for vertical spaces and 1700 for horizontal spaces (with the upper surface being warmer than the lower surface).¹ Hence, the maximum spacing between the hardware and the MLI containment blanket without free convection occurring is 2.4 cm for the sides and 2.3 cm for the top or bottom. As long as the MLI containment blanket is spaced within these limits, the CO₂ gap should behave as bulk insulation.

Use of CO₂ in ground test vacuum chambers presents a formidable challenge when the chamber pressure is low (in this case, 8 torr) and the CO₂ temperature must be maintained below -90°C. To avoid these issues, thermal engineers opt for gaseous nitrogen (GN₂). The analogous GrPr derivation can be performed for GN₂ in Earth ground testing. Free convection effects are negligible provided that the containment MLI is spaced no more than 7.9 cm and 7.5 cm for sides and top or bottom, respectively.

PREDICTED PERFORMANCE

With the absence of free convection, the effective conductance for a CO₂ gap insulation system around an electronics box becomes a straightforward calculation. In terms of heat transfer through this insulation system, two modes should be considered: conduction and radiation. The conduction heat flow per box face can be determined by:

$$Q_{i,c} = G_i(T_{\text{box}} - T_{i,o}), \text{ where}$$

$$G_i = k_{\text{CO}_2} \left(\frac{L_1 L_2}{\delta} + 0.54(L_1 + L_2)\delta + 0.2\delta \right)$$

where k_{CO_2} is the thermal conductivity of CO₂, L_1 and L_2 are the dimensions of the box face, δ is the insulation gap width, T_{box} is the PEB average temperature, and $T_{i,o}$ is the outer insulation temperature

The radiation heat flow per box face can be approximated by infinite parallel plates using the appropriate averaged area:

$$Q_{i,r} = \frac{A_{\text{avg}} \sigma}{\frac{1}{\epsilon_{\text{box}}} + \frac{1}{\epsilon_{i,i}} - 1} (T_{\text{box}}^4 - T_{i,i}^4)$$

where, A_{avg} is the average area of the box insulation faces, and ϵ_{box} , $\epsilon_{i,i}$, T_{box} , and $T_{i,i}$ are the emissivities and the temperatures of the box and inner insulation, respectively.

Since Martian nighttime power resources are limited, understanding the heat loss through the insulation is crucial. Again, assuming that the electronics box is maintained at its minimum allowable flight non-operating temperature limit of -50°C while the Martian atmosphere temperature is at its minimum nighttime value of -93°C, the total amount of heat loss through the CO₂ gap insulation is 3.2 watts. A comparable estimation for fiberglass batt insulation reveals that 4.5 watts are lost through the insulation.

COMPARATIVE TESTING

As mentioned previously, JPL engineers conducted thermal performance testing of the MSP'01 PEB with fiberglass batt insulation.

Fiberglass Batt Insulation

Aircraft builders have used the fiberglass batt insulation for sound attenuation as well as for thermal barriers.² For space applications, the shaped insulation can be fabricated from a mold that is furnace-fired. A five-layer multi-layer insulation blanket is attached to the exterior of the batt insulation for ease of handling. The MSP'01 PEB fiberglass insulation is shown in Fig 4.

Thermal Performance Testing of Fiberglass Batt Insulation

The initial purpose of this testing was to characterize heat loss through the insulation as well as heat losses through other paths such as thermal isolation mount and cabling. JPL engineers conducted these tests in May 1999.³ The test was conducted in a 3-foot diameter horizontal vacuum chambers at JPL (see Fig

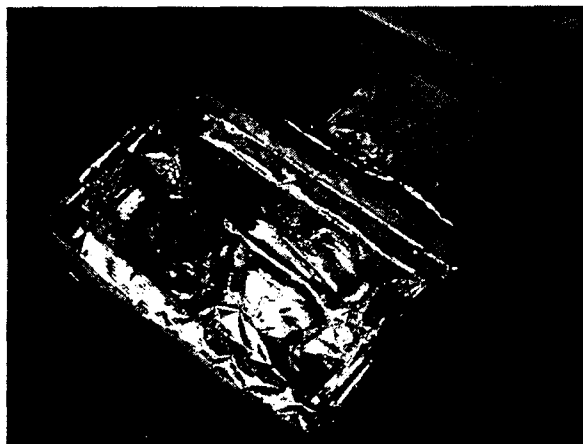


Figure 4 - PEB fiberglass batt insulation with Kapton outer layer, looking from mounting interface toward the top and bottom close-out placed to the side

5). The PEB was mounted to a heat exchanger that simulated the mounting interface. The Martian atmosphere was simulated by first achieving a high vacuum ($<1 \times 10^{-4}$ torr) and then backfilling with GN_2 . GN_2 was used in place of CO_2 since maintenance of 8 torr at low temperature is very challenging with CO_2 . The chamber shroud was used to simulate the effective Martian sky temperature. Much of the characterization was obtained for a PEB maintained at -50°C mounted to an -85°C interface and exposed to a GN_2 temperature of -93°C . Sufficient testing was conducted to determine heat flow across the fiberglass batt insulation (see Table 1).

Table 1 – Total Insulation Heat Loss Test Results for PEB @ -50°C *

Insulation	Total Insulation Heat Loss, watts	
	Test	Prediction
Fiberglass batt	3.9	4.5
CO_2 gap	2.4 [†]	3.2
GN_2 gap	5.3	8.7

* PEB maintained at -50°C on a -85°C mounting interface within a -93°C atmosphere

[†] Heat loss extrapolated from PEB at 0°C test data

Thermal Performance Testing of CO_2 Gap Insulation

The primary objectives of the gap insulation testing were to compare the heat transfer across the insulation to the previous fiberglass batt insulation testing, and to determine Martian surface performance. To this end, the same test article, test setup, and approach were used. The first test cases were identical to the fiberglass batt testing, however GN_2 gap insulation was used instead. The total heat loss through the GN_2 gap insulation (i.e., conductive and radiative heat paths) is tabulated in Table 1. The second series of test cases investigated insulation performance

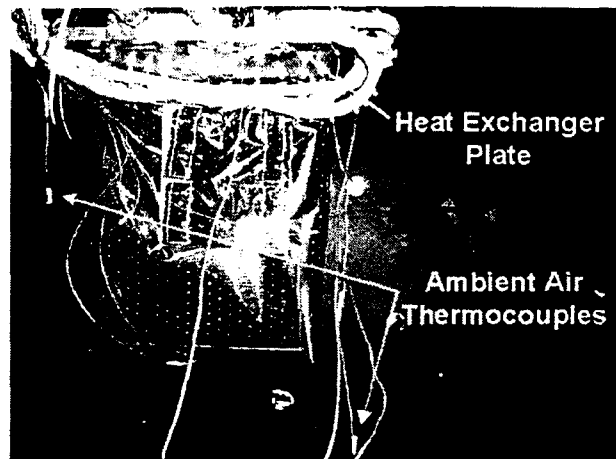


Figure 5 - PEB insulation test setup in a JPL 3-foot vacuum chamber

under identical conditions using CO_2 and GN_2 as the gap insulation. In order to avoid difficulties with CO_2 , the PEB was maintained at a much warmer temperature of 0°C mounted to a -33°C interface and exposed to a simulated Martian atmospheric temperature of -39°C . These total heat loss through the insulation results are shown in Table 2. This test data was used to analytically estimate CO_2 gap insulation total heat loss for conditions that were identical to the fiberglass batt testing. For comparative purposes, this CO_2 gap insulation total heat loss is shown in Table 1.

Table 2 - Total Insulation Heat Loss Test Results for PEB @ 0°C *

Insulation	Total Insulation Heat Loss, watts	
CO_2 Gap		3.9
GN_2 Gap		7.1

* PEB maintained at 0°C on a -33°C mounting interface within a -39°C atmosphere

Comparison of Test Results

For the expected coldest nighttime conditions for the MSP'01 Lander mission, Table 1 indicates that the CO_2 gap insulation demonstrates better insulating performance

than fiberglass batt insulation. The 1.6 watt heat loss difference between fiberglass batt and CO₂ gap insulation represents a potential nighttime battery energy savings of 22 W-hr (assuming a Martian nighttime duration of 14 hours). The comparative total heat loss through the insulation trends between the CO₂ and GN₂ gap insulations that are seen in Table 1 are reinforced in Table 2 for a warmer PEB temperature.

OTHER MAJOR METRICS

Besides insulating performance, there are other factors that are used in the selection of an insulation system: mass, cost, and delivery schedule. Because of its relatively simple and innovative design, the CO₂ gap insulation demonstrates distinct mass, cost, and delivery schedule advantages. Since the Martian atmosphere provides the insulating medium (CO₂), its total mass is 60% less than the fiberglass batt insulation. The fiberglass batt insulation shaping process involves the fabrication of inner- and outer-mold line tool, which results in a labor-intensive effort. The CO₂ gap insulation fabrication process is very similar to current MLI blanketing process. Hence, this insulation can be fabricated and installed as late as possible in the mechanical integration process. In addition, the CO₂ gap insulation is more accommodating for late changes since the stood-off radiation barrier can be more readily reshaped. Overall, the CO₂ gap insulation is 33% less costly and 75% faster in delivery schedule than the proposed fiberglass batt insulation for the MSP'01 PEB. These metrics are summarized in Table 3.

SUMMARY

JPL engineers have developed and tested a novel insulation system for Martian surface applications. This insulation relies upon the readily available CO₂ from the

Table 3 – Summary of other important metrics for insulation selection

Metric	Fiberglass Batt Insulation	CO ₂ Gap Insulation
Mass	~0.5 kg	~0.2 kg
Fabrication Cost	\$9K	\$6K
Delivery Time	1 month	~1 week

Martian atmosphere. Since this insulation scheme relies on known MLI blanketing processes, it can be applied to a variety of hardware geometries. Its insulating performance exceeds that of fiberglass batt by 38% for the coldest Martian nighttime condition expected for the recently cancelled MSP'01 Lander mission. In other important metrics, this insulation was 60% less massive, 33% less costly, and 75% faster in delivery schedule than fiberglass batt insulation for the specific MSP'01 PEB application.

The analytical estimates for the fiberglass batt and CO₂ gap insulations were in fair agreement with test (see Table 1). The comparison between analysis and test demonstrates that the analytical approach is conservative (i.e., over estimates total heat loss). Improved agreement between analysis and test will be necessary before the analytical model is used in flight design applications.

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